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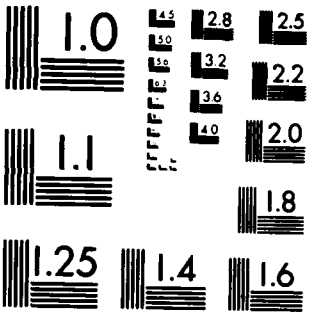

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A PILOTED SIMULATOR INVESTIGATION OF SIDE-STICK CONTROLLER/STABILITY AND CONTROL AUGMENTATION SYSTEM REQUIREMENTS FOR HELICOPTER VISUAL FLIGHT TASKS

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ABSTRACT

A piloted simulator experiment was conducted to assess the effects of side-stick controller characteristics and level of stability and control augmentation on handling qualities for several low-altitude control tasks. Visual flight tasks were simulated using four-window computer-generated imagery depicting either a nap-of-the-earth course or a runway with obstacles positioned to provide a slalom course. Both low speed and forward flight control laws were implemented, and a method for automatically switching control modes was developed. Variations in force-deflection characteristics and the number of axes controlled through an integrated side-stick were investigated. With high levels of stability and control augmentation, a four-axis controller with small-deflection in all four axes achieved satisfactory handling qualities for low-speed tasks. However, the four-axis configuration yielded degraded handling qualities compared to separated controllers for multi-axis control tasks and when reduced levels of stability and control augmentation were provided.

INTRODUCTION

As part of the Army's Advanced Digital/Optical Control System (ADOCS) program, a series of piloted simulations has been conducted to develop the integrated side-stick controller characteristics and flight control laws to be implemented on the ADOCS demonstrator helicopter. Two major simulation phases have been completed between January 1981 and December 1982 under the Advanced Cockpit Controls/Advanced Flight Control System (ACC/AFCS) element of the ADOCS program.

Phase 1 was conducted at the Boeing Vertol Flight Simulation Facility which provides a wide field-of-view visual display and limited six degree-of-freedom motion cues. This first simulation phase concentrated on the critical low-speed, low-altitude portions of the scout/attack helicopter mission and evaluated tasks under both visual and instrument meteorological conditions (VMC and IMC, respectively).

The Phase 2 simulation experiment, the subject of this paper, was performed at the NASA Ames Vertical Motion Simulator (VMS) Facility which includes a six degree-of-freedom large motion base simulator and a four-window computer generated visual display system. Phase 2 evaluated handling qualities under VMC and emphasized tasks which represented elements of the entire scout/attack-helicopter mission including low-speed, transition, and forward flight.

Results from the Phase 1 simulation provided a significant amount of information on the interactive effects of side-stick controller characteristics and level of stability and control augmentation on scout/ attack helicopter handling qualities. As reported in Reference 1, a four-axis side-stick controller having limited motion in the pitch and roll axes was preferred to a stiff four-axis controller for nap-of-the-earth (NOE) maneuvering and precision hover tasks. However, for most of the tasks investigated, the preferred four-axis configuration resulted in degraded handling qualities when compared to controller configurations having separated left-hand control of the vertical axis using a standard collective lever configured as a force controller.

For all the low speed VMC tasks and controller configurations evaluated during the Phase 1 simulation, satisfactory (Level 1) handling qualities were obtained with control laws consisting of: (1) attitude command/linear velocity stabilization in the longitudinal and lateral axes, (2) yaw rate command/heading stabilization in the directional axis, and (3) vertical velocity command/altitude stabilization in the vertical axis. A reduction in the level of stability augmentation to attitude stabilization in the longitudinal and lateral axes resulted in a degradation to acceptable (Level 2) handling qualities for the same tasks with all four-axis controller configurations; however, with an attitude

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stabilization level, separated vertical and/or directional controllers yielded satisfactory (Level 1) handling qualities.

Phase 1 results were validated during Phase 2 using the NASA Ames simulator facility which provides a higher fidelity motion cue environment. In addition, an assessment of the effects of large motion on pilot kinesthetic coupling with various side-stick controller configurations was conducted. Based on Phase 1 results, it was decided to investigate the possible benefit of improved vertical axis control through a four-axis controller with limited deflection in all axes. A new grip, similar to the grip used in the Reference 3 program, was included to minimize the vertical-to-longitudinal-and-lateral control coupling inherent in the original grip. Separate left-hand control of the vertical axis through a side-stick controller was also evaluated.

Accordingly, the primary objectives of the Phase 2 simulation experiment were: (1) to assess the effects of a more valid representation of aircraft motion, (2) to evaluate new side-stick controller configurations, including a four-axis controller with limited deflection in all axes, and (3) to investigate forward flight control laws, including blending of control modes between low-speed and forward flight.

EXPERIMENT DESIGN

The major variables selected for investigation were as follows:

(1) Controllers: Force-deflection characteristics and number of axes controlled through a multi-axis side-stick controller

(2) Stability and control augmentation systems: Level of stabilization and control response type

(3) Evaluation tasks: Low speed and high speed tasks requiring both precision of control and maneuverability.

CONTROLLERS

Previous research programs, using both ground- and in-flight simulation (Reference 2 and 3, respectively), have demonstrated a degradation in handling qualities which occurs as a result of integration of control over four aircraft axes into a single stiff side-stick controller. These handling qualities experiments evaluated tasks which comprise elements of the maneuvers required for NOE flight. A major difficulty with the use of the side-stick controller was the pilots' inability to decouple their control actions; inadvertent inputs into other controlled axes degraded system performance and markedly increased pilot workload. Both experiments showed some benefit of separating the vertical control axis from the remaining three.

Similar handling qualities problems with the identical stiff four-axis controller were demonstrated during the Reference 1 experiments. In addition, slightly improved handling qualities for specific tasks resulted from adding limited deflection to the longitudinal and lateral axes of the side-stick.

The Phase 2 simulation experiment reported herein continued the investigation of the effects of controller force-deflection characteristics and the level of integration of controlled axes on a single controller.

Three four-axis side-stick controllers (Figure 1) were evaluated:

(1) Controller 1: A stiff force controller identical to the controllers investigated in References 1, 2 and 3.

(2) Controller 2: A force controller with limited deflection in the longitudinal and lateral axes (small-deflection configuration 2 of Reference 1).

(3) Controller 3: A force controller with limited deflection in all four axes.

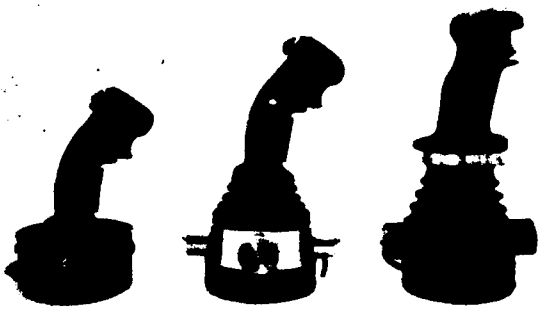

Figure 1. Four-Axis Side-Stick Controllers

All three controllers were manufactured by Measurement Systems, Inc., Norwalk, Connecticut and are base-pivot type for pitch and roll inputs; fore-and-aft force produces longitudinal control input, and right-left force produces lateral control input. Yaw control is obtained by twisting about the grip centerline and vertical control through application of up-down forces. Table 1 presents the force characteristics of the three controllers.

The grips provided with Controllers 1 and 2 are identical; Controller 3 was equipped with a modified grip based upon the findings of Reference 3. This particular grip was designed to improve the pilot's ability to apply single-axis vertical and directional control inputs and to minimize inter-axis coupling of these inputs.

TABLE 1. FOUR-AXIS SIDE-STICK CONTROLLER FORCE/ DEFLECTION CHARACTERISTICS

4-AXIS CONTROLLER CONFIGURATION		OPERATING FORCE LINEAR RANGE ±				MAXIMUM DEFLECTION				FORCE/DEFLECTION GRADIENT			
NO.	DESCRIPTION	X LONG. LB	Y LAT LB	Z VERT LB	ψ YAW IN.-LB	X LONG. DEG	Y LAT DEG	Z VERT IN.	ψ YAW DEG	X LONG. LB/DEG	Y LAT LB/DEG	Z VERT LB/IN.	ψ YAW IN.-LB/DEG
1	STIFF STICK	30	30	40	60	0.5	0.5	–	–	60	60	–	–
2	SMALL DEFLECTION PITCH/ROLL	16	12	40	60	0.3	0.3	0.15	0.6	1.82	1.45	267.0	10.0
3	SMALL DEFLECTION ALL AXES	12	12	+24 −21	30	0.6	0.6	0.35	10.0	1.82	1.82	+65 −85	3.0

Three different side-stick configurations were evaluated using these controllers, as illustrated in Figure 2: (1) (4+0) - a right-hand four-axis controller, (2) $(3+1)_C$ - a right-hand three-axis controller and a left-hand vertical (collective) controller, and (3) (2+1+1) - a right-hand two-axis controller, a left-hand vertical controller, and pedals configured as a force controller for directional inputs. Left-hand side-stick control of the vertical axis was accomplished through the longitudinal control axis of either Controller 1 or 2. The directional pedals evaluated as part of the (2+1+1) configuration had a force-deflection gradient of 40 lbs/inch and a breakout force of 6.0 lbs.

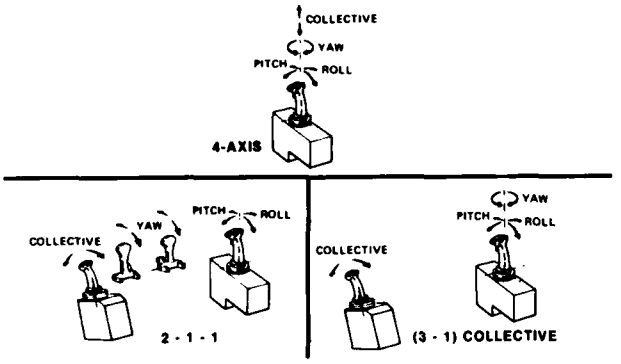

Figure 2. Controller Configurations

The various controller configurations are identified by numerical subscripts to indicate both the right-hand and left-hand (where applicable) controllers being evaluated. For example, $(4+0)_3$ indicates that Controller 3 was evaluated as a right-hand four-axis device while $(3+1)_{C3,2}$ is the identifier for a configuration consisting of Controller 3 on the right as a three-axis device and Controller 2 on the left for collective control.

STABILITY AND CONTROL CHARACTERISTICS

Simulation of the baseline flight vehicle was provided by a generic single main rotor helicopter model--which included three-degree-of-freedom tip-path plane dynamics, six-degree-of-freedom rigid-body dynamics, and main- and tail-rotor RPM degrees of freedom--configured to represent the UH-60A Black Hawk helicopter.

A description of the generic helicopter model is given in Reference 4. The model used includes a canted tail rotor, UH-60A fuselage aerodynamics, control mixing, and a moving stabilator and stabilator control system. Data used to implement these modifications were derived from Reference 5. Model validation was accomplished by a comparison of model trim data and small perturbation, six-degree-of-freedom, stability and control derivatives with the corresponding data generated from both the Reference 5 model and the simulation model used in the Reference 1 investigations.

Figure 3 presents a block diagram of the flight control system design concept developed for the ADOCS Demonstrator Program. The primary flight control system (PFCS) was designed to yield satisfactory unaugmented flight by providing feed-forward command augmentation and shaping. The advanced flight control system (AFCS) included both stabilization feedback loops and a feed-forward control response model. Stabilization feedback loops were designed solely for maximum gust and upset rejection; no compromise for control response was necessary. Use of a control response model allowed the shaping of the short- and long-term response to the pilot's control inputs independent of the stabilization level.

Primary Flight Control System (PFCS)

As indicated in Figure 4, a pilot force command signal was provided to each PFCS axis. The signal was shaped, adjusted in gain, passed through a derivative rate limiter, and fed to the AFCS command model and to the primary UH-60A flight control system through a shaping network. Limiting of the AFCS output was also a function of the PFCS but was not incorporated for this experiment.

Force command signal quantization was varied over a 12-bit to 6-bit range during initial experiments. The resolution provided by 8-bit quantization of each force command input was sufficient to ensure that no degradation in aircraft response was perceptible to the pilot; the roll axis was the most sensitive to reduction in resolution and yielded the 8-bit quantization limit. This quantization value was used in each axis for the remainder of the experiment.

Non-linear command shaping was provided in each axis by a dead-zone and a control sensitivity function made up of three segments. In all axes less sensitivity was provided for lower values of control force. In the longitudinal and lateral axes, the shaping function was symmetrical about zero force input; the vertical and directional shaping functions were asymmetric to compensate for the comparative difficulty of exerting a downward versus an upward force and a right versus a left twist, respectively, on a right-hand side-stick controller.

A derivative rate limiter was provided in each axis to limit the magnitude of initial acceleration response during rapid maneuvers when using a force controller. Characteristics of the limiter were individually selected for each axis so as to reduce peak responses for large control inputs without affecting control precision for small force inputs.

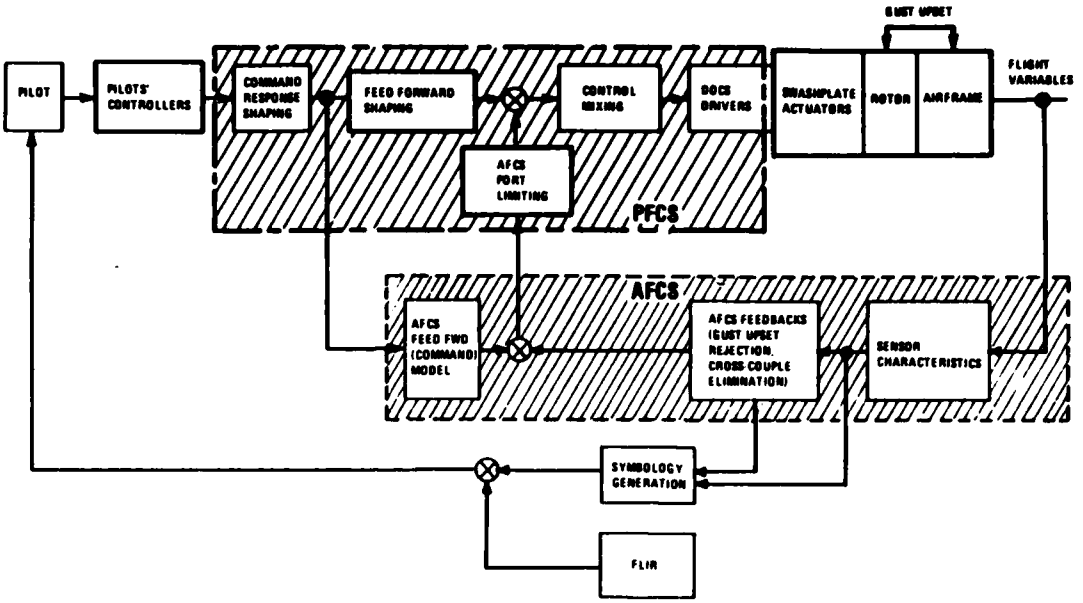

Figure 3. ADOCS Demonstrator Flight Control System Concept

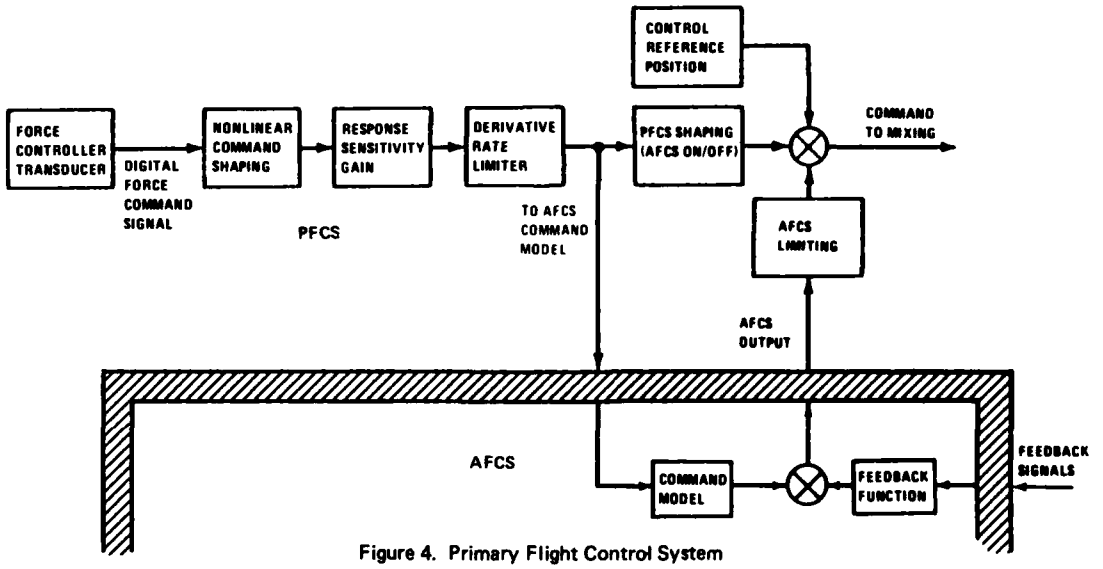

Figure 4. Primary Flight Control System

Forward path lead-lag shaping was provided with AFCS operating; the lead and lag time constants were selected to match the desired command model and basic helicopter response characteristics to reduce the magnitude of AFCS output during normal maneuvers.

Advanced Flight Control System (AFCS)

The AFCS model implemented for the Reference 1 experiments was modified for this experiment to include additional feedback and feedforward paths required for forward flight control laws. Airspeed and lateral acceleration stabilization signals and cross-axis control paths required for decoupling and automatic turn coordination were added to the original AFCS, designed primarily for hover and low speed flight.

In the longitudinal AFCS, linear velocity stabilization was provided by a longitudinal ground speed signal when airspeed decreased below 40 knots and by a longitudinal airspeed signal when airspeed increased above 45 knots. Switching between the two signals was transient-free.

The lateral AFCS was implemented for this experiment as indicated in Figure 5. In order to switch between a roll attitude command/lateral velocity stabilization system at low speed and a roll rate command/attitude hold system for higher speed maneuvering flight, a selectable hybrid lateral AFCS was provided. The indicated gain changes were ramped over a five-second time period and were initiated by the following control mode logic. The switch to the rate command system was accomplished when airspeed exceeded 45 knots if roll rate was less than 1.0 deg/sec. If the pilot was holding a bank angle force command at this time, the aircraft would respond to satisfy the commanded roll rate. In order to minimize switching transients when decelerating in a turn, logic delayed switching to an attitude command system below 40 knots until bank angle was less than 3.0 degrees and roll rate was less than 1.0 deg/sec.

A cross-axis command path to the directional AFCS was also provided (Figure 5); the commanded bank angle was used to calculate a yaw rate command as a function of airspeed to provide for automatic turn coordination (Figure 6).

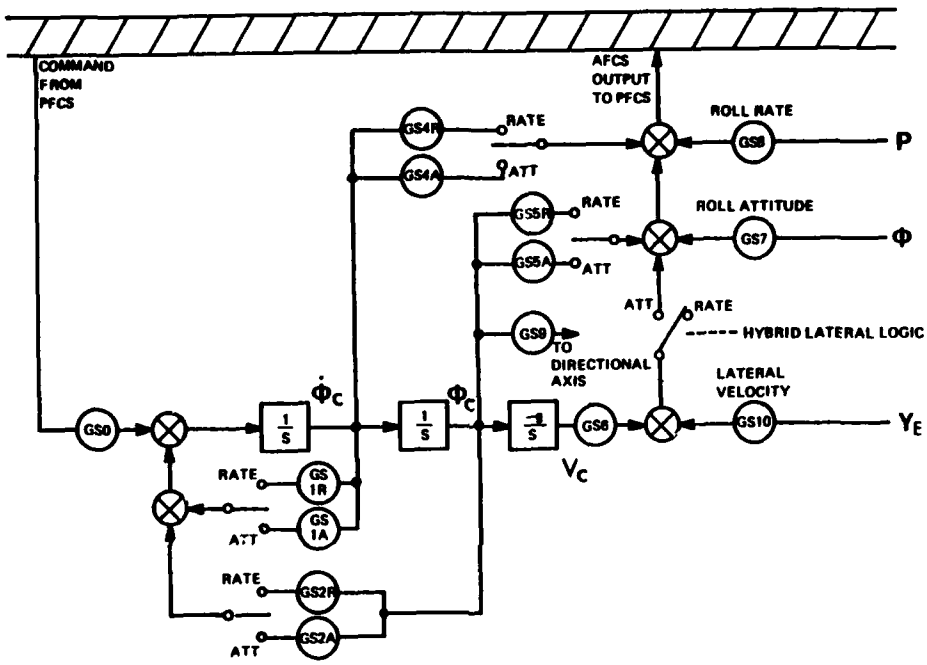

Figure 5. Advanced Flight Control System – Lateral Axis

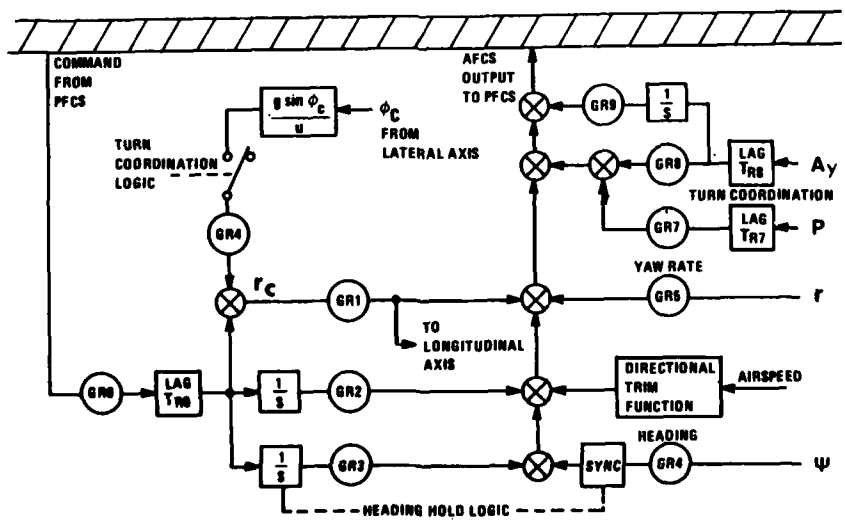

Figure 6. Advanced Flight Control System – Directional Axis

As indicated in Figure 6, the selectable turn coordination mode in the directional AFCS was achieved by a combination of integral-plus-proportional lateral acceleration feedback, roll rate feedback, and the yaw rate command feedforward path. If selected, turn coordination was activated automatically when airspeed exceeded 50 knots and a roll rate was commanded by a lateral force input. While turn coordination was operating, the heading hold function was disengaged in turning flight. Turn coordination remained on, and heading hold off, until the aircraft was commanded to a bank angle of less than 3.0 degrees and both roll rate and yaw rate were less than 1.0 deg/sec. Long-term heading hold stabilization was provided full-time, if selected, and turn coordination disengaged for airspeeds below 50 knots. However, during a decelerating turn maneuver from forward flight, the heading hold mode would not engage until the above requirements on roll rate, yaw rate, and roll attitude were satisfied.

The vertical AFCS was modified to include gain scheduling as a function of airspeed for the altitude and altitude rate feedback paths to achieve tight altitude hold for precision hover tasks and lower stabilization gains during high speed flight. Command model gains were also altered appropriately to provide the desired vertical response to control inputs at all airspeeds.

The generic AFCS variations investigated in this experiment are presented in Table 2. An explanation of the nomenclature used to identify each AFCS configuration follows:

- Pitch and Roll
  - AT/LV - Attitude command, Velocity stabilization.
  - AT/AT - Attitude command, Attitude stabilization.
  - RA/AT - Rate command, Attitude stabilization.
  - AC/RA - Acceleration command, Rate stabilization.
- Yaw
  - $\dot{\psi}/\psi_H$ - Yaw rate command, Heading hold.
  - $\dot{\dot{\psi}}/\dot{\psi}$ - Yaw acceleration command, Yaw rate stabilization.
- Vertical
  - $\dot{h}/h_H$ - Vertical velocity command, Altitude hold.
  - $\dot{\dot{h}}/\dot{h}$ - Vertical acceleration command, Vertical velocity stabilization.

EVALUATION TASKS

Since the Reference 1 experiments concentrated on the hover and low-speed segments of the scout/attack helicopter mission, a purpose of this simulation was to investigate representative VMC forward flight tasks and the transition to and from hover. To provide a basis for comparison between this experiment and the Reference 1 results, the identical NOE task conducted under VMC in those experiments was repeated for several of the controller/AFCS configurations.

TABLE 2. GENERIC AFCS CONFIGURATION MATRIX

RESPONSE COMMAND MODEL	STABILIZATION LEVEL: LONGITUDINAL/LATERAL RA	AT	LV	LP	DIRECTIONAL RA	AT	VERTICAL LV	LP
AC	●				●	○		
RA	○	●	○		○	●	NA	
AT		●	●					
LA					NA		●	○
LV			○	○			○	●

● CONFIGURATIONS EVALUATED IN CURRENT EXPERIMENT (PHASE 2)

○ ADDITIONAL CONFIGURATIONS EVALUATED IN PREVIOUS EXPERIMENT (PHASE 1)

	PITCH/ ROLL	YAW	VERTICAL
ANGULAR ACCELERATION	AC	$\ddot{\psi}$	-
ANGULAR RATE	RA	$\dot{\psi}$	-
ANGULAR ATTITUDE	AT	ψ_H	-
LINEAR ACCELERATION	LA	-	$\ddot{h}$
LINEAR VELOCITY	LV	-	$\dot{h}$
LINEAR POSITION	LP	-	h_H

EXAMPLE:

RA/AT - ANGULAR RATE COMMAND/ATTITUDE STABILIZATION

$\dot{\psi}/\psi_H$ - YAW RATE COMMAND/HEADING HOLD

Certain configurations were evaluated under a specified level of wind and turbulence. The disturbance model utilized also included wind shear and is described in detail in Reference 6.

SUMMARY OF THE EXPERIMENT

The major variables--controller, AFCS, and evaluation task--selected for investigation are summarized in Figure 7.

CONDUCT OF THE EXPERIMENT

FACILITY DESCRIPTION

The Ames Research Center's Vertical Motion Simulator (VMS) Facility[7] has a six degree-of-freedom moving-base cab with 60 feet of available vertical travel (Figure 8). The simulator cab was modified to include a typical helicopter instrument panel and provisions for mounting the three candidate four-axis side-stick controllers on either the pilot's right- or left-hand side (Figure 9). Adjustable mounting brackets attached to the armrest of each controller allowed orientation of each side-stick controller for comfort and to minimize inter-axis control

inputs (Figure 10). In addition to the side-stick controllers, conventional helicopter directional pedals were implemented as small displacement force controllers. The visual scene was simulated using a four-window computer generated display system with two different data bases including: (1) an NOE course (Figure 11) designed as a replica of the terrain board NOE course utilized in the Reference 1 simulations, and (2) an airport runway (Figure 12) with evenly spaced obstacles positioned for a slalom course and approach to hover task. Figure 12 also demonstrates the location of the four windows with respect to the actual UH-60 pilot's field of view, expressed in degrees of arc from the design eye position.

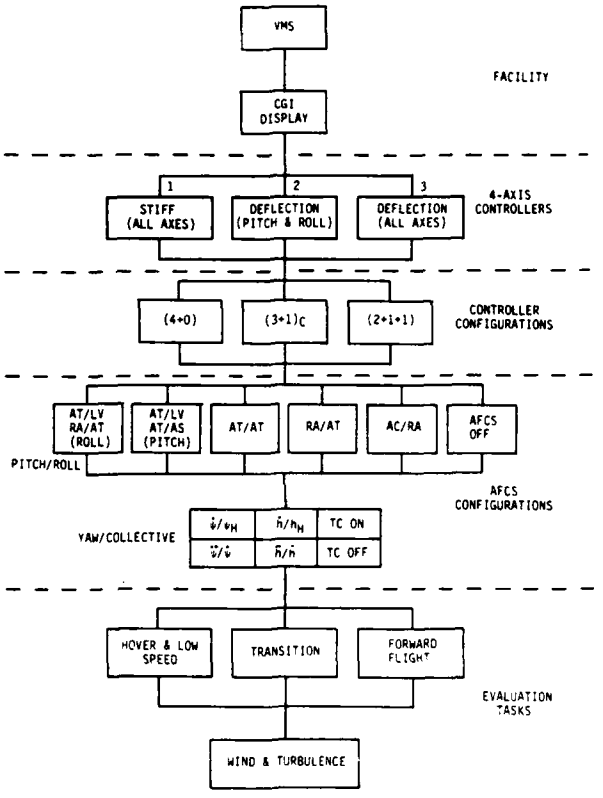

Figure 7. Elements of Simulation

EVALUATION TASKS

Evaluation of total system performance was accomplished using three low speed and hover tasks -- NOE, precision hover, and bob-up (Figure 13); two high speed maneuvering tasks -- a 90- and 140 knot slalom (Figure 14); and two transition tasks -- a straight-in approach to hover and a turning approach to hover (Figure 15). No secondary tasks (e.g., armament, communication, or navigation system management) were required of the pilot during the evaluations.

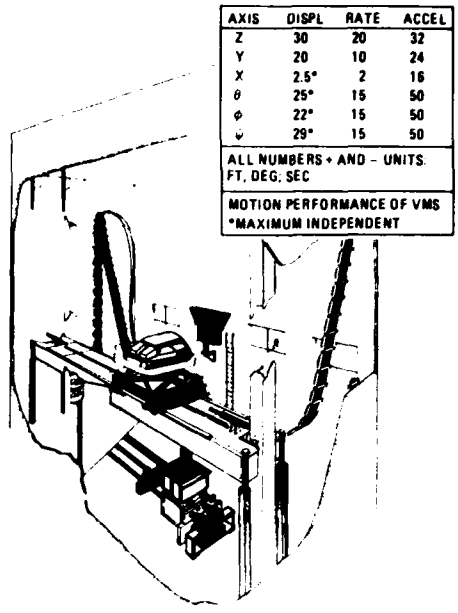

Figure 8. NASA Ames Vertical Motion Simulator (VMS)

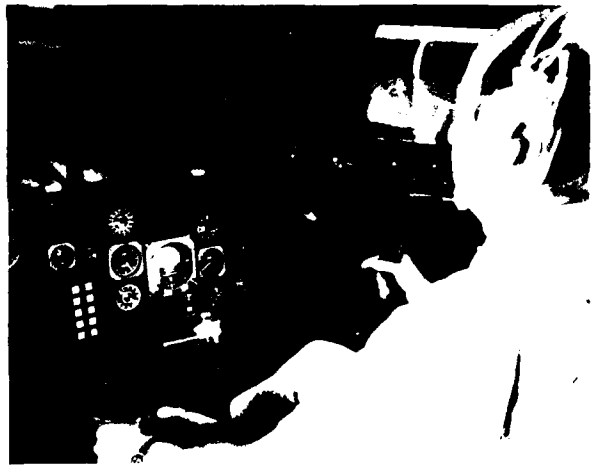

Figure 9. Simulator Cockpit and Controller Installation

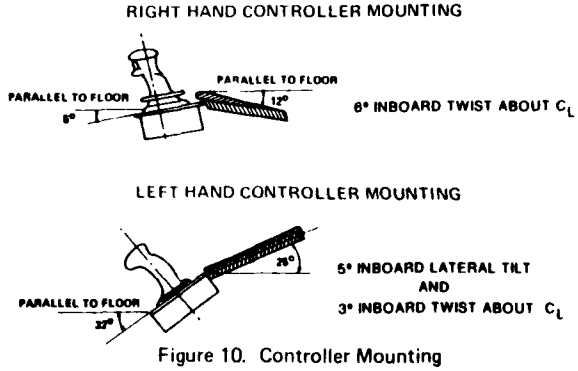

Figure 10. Controller Mounting

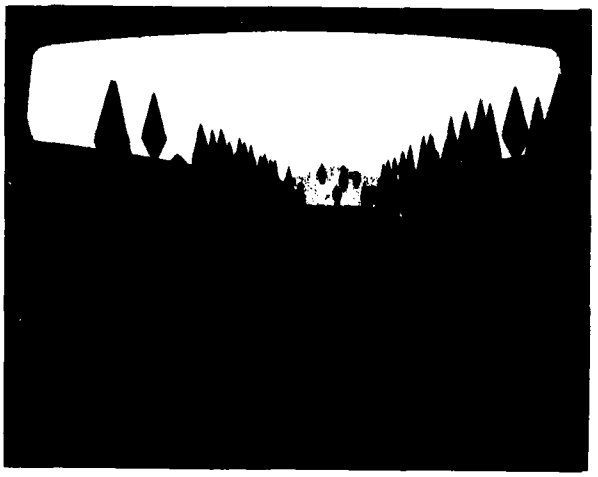

Figure 11. CGI Display – Nap-of-the-Earth (NOE) Course

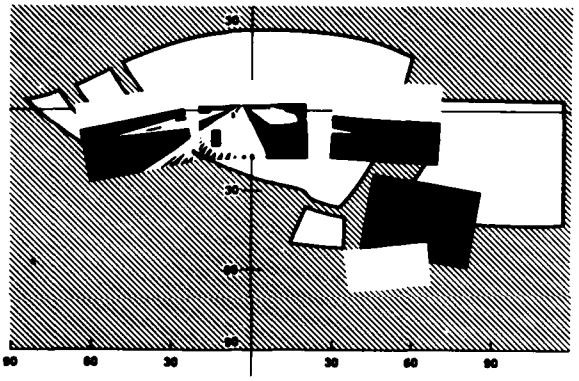

Figure 12. CGI Display – Slalom Course

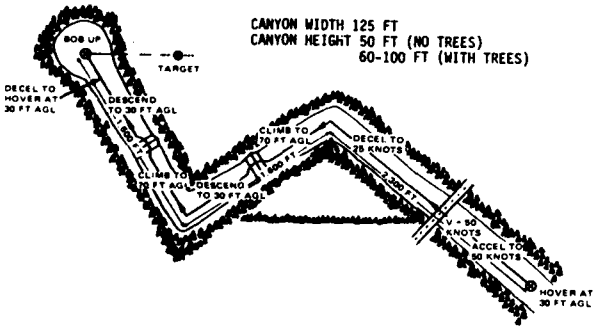

Figure 13. Low-Speed Evaluation Tasks – NOE, Precision Hover, and Bob-Up

Nap-of-the-Earth (NOE) - A multi-axis control task which required the pilot to fly through three legs of a narrow canyon (125 feet wide and 50 feet high) having two sharp turns (70° left and 80° right) and two obstacles (50 feet high), to reach a termination hover area. During the first leg of the course, an acceleration to 50 knots was performed before crossing a road, followed by a deceleration to 25 knots while maintaining a lateral ground track and an altitude of 30 feet. After executing a coordinated left turn to enter the second leg, the pilot was required to control altitude to fly over an obstacle and remask to 30 feet in as short a time as possible while attempting to maintain an airspeed of 25 knots. Following a sharp right turn, the pilot flew over a second obstacle, restored altitude back to 30 feet, and decelerated to a hover point in the termination area.

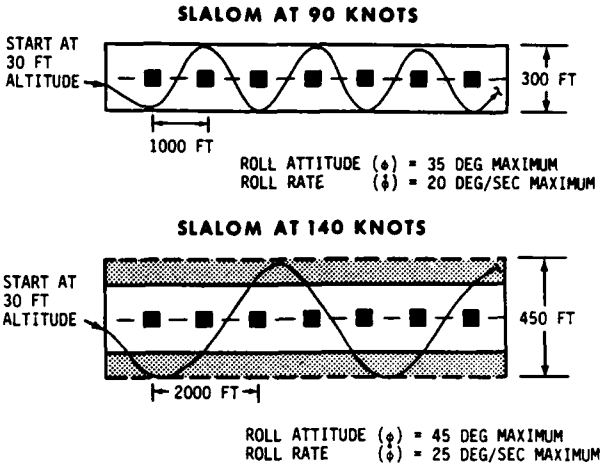

Figure 14. High-Speed Slalom Tasks

Precision Hover - This task required the pilot to descend from a 30 foot altitude to a 5 foot hover height while aligning the helicopter with a rock located in the center of the bob-up area. A precision hover was maintained with the rock positioned in the lower right-hand window.

Bob-Up - A multi-axis task which consisted of a vertical unmask maneuver from 25 feet to 100 feet, a heading turn to acquire a target, and a vertical remask to the original hover height. The pilot was required to hold a fixed horizontal ground position throughout the vertical unmask/remask and heading turn maneuvers.

Slalom - A high speed lateral avoidance task which required the pilot to maneuver around 50 foot high obstacles placed 1000 feet apart on the runway centerline while maintaining constant airspeed (90 knots or 140 knots), altitude (30 feet AGL), and a specific lateral ground track determined by runway width and obstacle separation.

Straight-In Approach to Hover - The task started with the helicopter in level flight at 100 knots and 275 feet AGL. The pilot was required to descend and decelerate on a 4° glideslope over a horizontal distance of 4000 feet to a 25 foot hover point in front of a 50 foot obstacle.

Figure 15a. Straight-In Approach to Hover

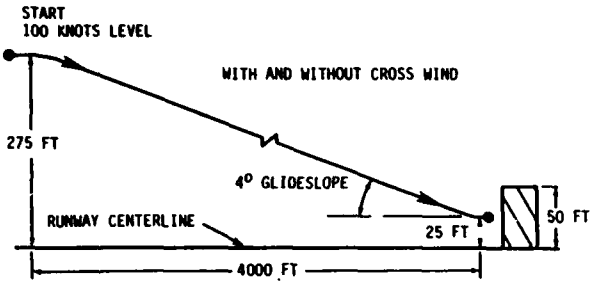

Figure 15b. Turning Approach to Hover

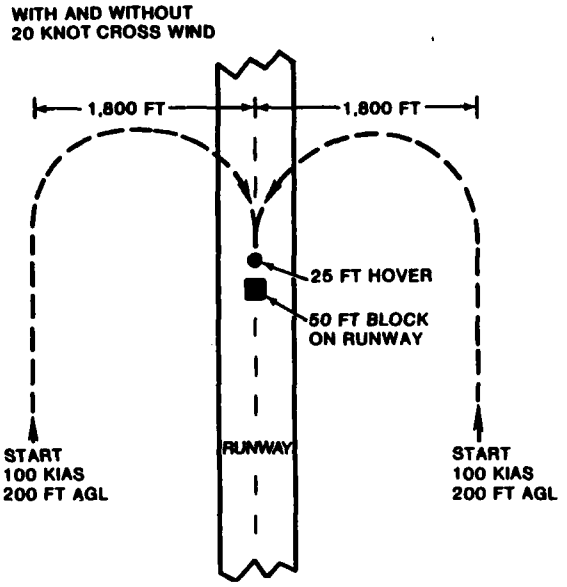

Figure 15. Transition Evaluation Tasks

Turning Approach to Hover - A forward flight to low speed transition task that required the pilot to perform a left or right descending, decelerating turn and arrive at a 25 foot hover in front of a 50 foot obstacle on the runway centerline.

EVALUATION PILOTS' BACKGROUND AND EXPERIENCE

Four experimental test pilots participated in this simulation study--one each from Boeing-Vertol, NASA, the U.S. Army, and the National Aeronautical Establishment (NAE) of Canada. A summary of their flight time and related experience in side-stick controller development is presented in Table 3. Three of the evaluation pilots, (A, C, and D), participated in the previous ADOCS simulation study (Reference 1). Pilot A was the primary evaluator for this experiment. A total of 66 simulation flight hours and 1250 pilot evaluation data runs were accumulated.

TABLE 3. SUMMARY OF PILOT EXPERIENCE

PILOT	AFFILIATION	FLIGHT TIME (HOURS) HELICOPTER/ FIXED-WING	FLIGHT TIME (HOURS) TOTAL	RELATED EXPERIENCE SIDE-STICK CONTROLLER DEVELOPMENT FLIGHT TEST	RELATED EXPERIENCE SIDE-STICK CONTROLLER DEVELOPMENT SIMULATION
A	BOEING VERTOL	3,000 (H) 2,000 (F)	6,000	X	X
B	NAE CANADA	900 (H) 6,400 (F)	7,400	X	X
C	NASA AMES	2,500 (H) 800 (F)	3,300	X	X
D	U.S. ARMY	2,400 (H) 1,000 (F)	3,400	-	X

DATA COLLECTION AND ANALYSIS

Both pilot evaluation data and quantitative system performance data were collected. The pilot evaluation data consist of Cooper-Harper handling qualities ratings and tape-recorded pilot commentary. At the end of each evaluation run the pilot assigned a single numerical Cooper-Harper rating to the particular controller/AFCS/task combination under investigation. In addition, the pilot was asked to provide commentary to help identify those aspects of the system that most heavily influenced the rating. The quantitative system performance data consist of magnetic tape recordings of specified flight parameters and statistical data, which include mean and standard deviations of helicopter flight parameters relative to a reference hover position or desired flight path. These statistical data will be used as measures of pilot workload and system performance.

OTHER EXPERIMENTAL CONSIDERATIONS

In order to maximize the number of pilot evaluations in a typical simulation session, the controllers used on the pilot's right- and left-hand side and the task performed by the pilot remained fixed for the entire session. Changes to the controller configuration were made during a session only after investigating a full spectrum of AFCS characteristics for that particular configuration. In general, (4+0) configurations were evaluated first, $(3+1)_C$ second, and (2+1+1) last. Before each evaluation run, the pilots were told the command response type for each axis. They were not informed of the stabilization level in each axis or whether the automatic turn coordination feature was on or off. For the low speed tasks the pilots were given time to feel out the system before each data run, and for the high speed and transition tasks they were allowed to take a practice run, if desired.

EXPERIMENTAL RESULTS

Experimental results presented herein are based on an analysis of pilot ratings and comments. The results are summarized using averaged pilot ratings to illustrate general trends and explain pilot qualitative comments.

PHASE 1 AND PHASE 2 SIMULATION COMPARISON

Control Response Shaping

The improved motion and visual fidelity of the NASA Ames Vertical Motion Simulator necessitated adjustment to the PFCS command shaping characteristics developed during Phase 1 using the Boeing Vertol simulator. In order to provide acceptable response characteristics, both for small high-frequency precision control tasks and low-frequency larger amplitude maneuvers, it was necessary to add an additional third sensitivity gradient to the control response shaping functions primarily to reduce sensitivity in the low force region.

Figure 16 defines response shaping for the lateral and vertical axes, and compares the shaping developed during Phase 2 with the shaping developed in Phase 1. The shaping functions shown are for the 4-axis controller configurations. The shaping for the separate left-hand vertical controller and pedals for yaw control also required adjustment.

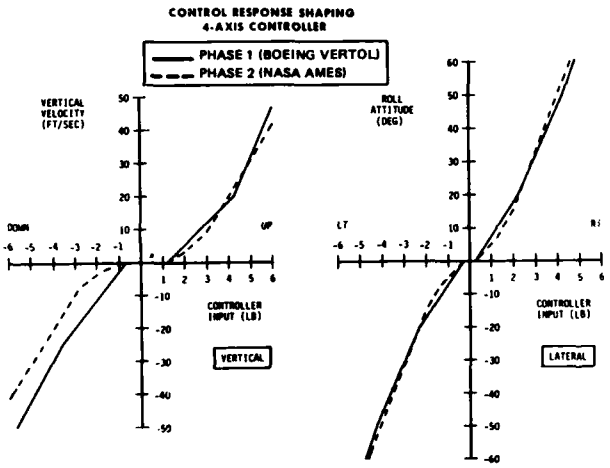

Figure 16. Control Response Shaping

The effect of the revised shaping in terms of pilot ratings is shown in Figure 17 for the NOE, precision hover and bob-up tasks. The improvement in the multi-axis NOE and the bob-up tasks was about one pilot rating point. An improvement of 1.5 to 2.0 rating points was achieved for the precision hover task. This result occurred because the precision hover task required lower force and higher frequency controller inputs in the region most affected by the shaping modifications. For all low speed tasks the modified shaping improved pilot ratings and provided Level 1 handling qualities for an attitude command system with velocity stabilization. Although the shaping was optimized primarily for the $(4+0)_3$ configuration, similar improvement in pilot performance was noted for the $(3+1)_{C3,2}$ controller configuration.

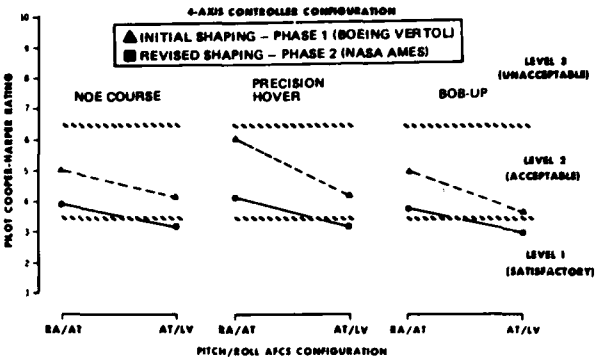

Figure 17. Effect of Control Response Shaping on Pilot Ratings

Visual Display/Motion System Effects

Phase 1 and Phase 2 data are compared in Figure 18 for Controller 2 in a 4-axis configuration $(4+0)_2$. Pilot ratings obtained from the Boeing Vertol and NASA Ames simulation facilities are similar for the multi-axis NOE maneuvering task, suggesting little effect of simulator on experiment results. However, pilot comments indicated that the NASA Ames CGI display provided improved visual cues compared to the Boeing Vertol television image, especially for maneuvers in the vertical axis. Qualitatively, the NOE task during Phase 2 seemed easier to fly at the same airspeed and control of height was improved. The pilots felt that the CGI terrain representation lacked granularity variation with altitude, but the strong motion and peripheral visual cues provided a very effective simulation of the NOE task.

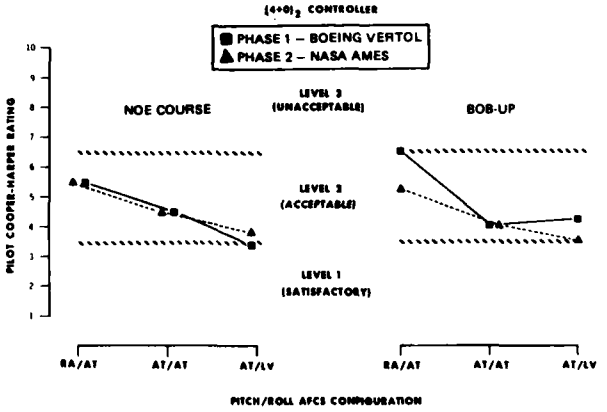

Figure 18. Simulation Data Comparison

Advantages of the CGI visual display system and stronger vertical motion cues were particularly evident during the bob-up task. Pilot ratings for the Phase 2 bob-up task were improved by over one rating point compared to Phase 1 data. Pilot comments indicated that the excellent color, clarity, and depth-of-field

of the CGI display afforded strong spatial position cues which improved the pilots' capability to perform the precision hover and bob-up tasks.

4-AXIS CONTROLLER EVALUATION

Three 4-axis side-stick controllers were evaluated in the (4+0) configuration for low speed tasks--NOE, precision hover, and bob-up. Figure 19 presents a comparison of pilot ratings obtained for the NOE task.

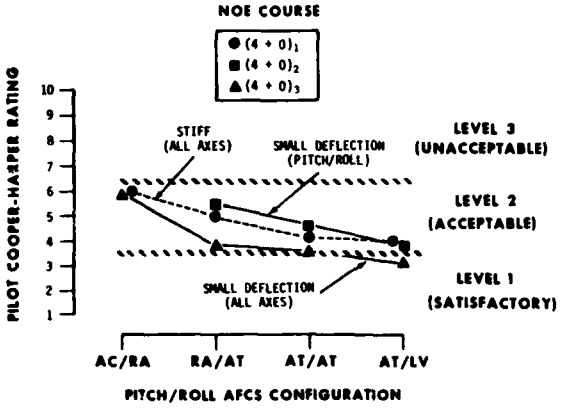

Figure 19. Comparison of 4-Axis Controller Configurations

Controller 3 (deflection in all axes) was unanimously preferred over both Controller 1 and Controller 2, and was the only 4-axis controller to receive Level 1 pilot ratings for the NOE task. All pilots felt that deflection in each control axis provided better definition of individual axis commands, reduced the tendency for inadvertent coupling of control inputs, and allowed precision control tasks to be performed more accurately.

Three minor problems were observed with the Controller 3 design during the course of testing:

(1) Maximum yaw axis control travel and forces were excessive for comfortable hand-wrist motion.

(2) Small mechanical free-play (manifested as a force deadband) degraded precise longitudinal axis control for small control inputs.

(3) Forward tilt of the grip with respect to controller mount introduced inadvertent roll/yaw coupling.

Pilot ratings with Controller 1 (stiff in all axes) were degraded approximately one rating point compared to Controller 3. It was more difficult with Controller 1 to modulate forces, particularly for high-frequency control tasks such as precision hover. This controller provided poor tactile feedback to the pilot and gave the feeling of not being 'tight' in the control loop, especially during large amplitude maneuvers. Compared to the other 4-axis controller configurations, Controller 1 exhibited more of a tendency toward pilot-induced oscillation (PIO) and was less tolerant to variations in response sensitivity required to suit individual pilot preferences.

Controller 2 (deflection in pitch and roll) was considered an improvement for pitch and roll control when compared to the stiff controller design. However, overall pilot ratings were slightly more degraded than Controller 1. Pilot comments indicated that poor control force harmony resulted from the combination of two stiff control axes and two deflection control axes on the same controller. Controller 2 had undesirable force modulation characteristics in yaw and collective. High frequency control was difficult in these axes and performance during the precision hover task, although better than the stiff controller (Controller 1), was marginally acceptable. Both Controller 1 and Controller 2 provided Level 2 handling qualities for all tasks and AFCS configurations.

One important anthropometric characteristic was common to all 4-axis controllers evaluated: the pitch and yaw orientation of the control and grip with respect to the armrest was critical to minimize pilot fatigue and reduce cross-axis coupling.

LEFT-HAND VERTICAL CONTROLLER EVALUATION

An objective of the Phase 2 experiment at NASA Ames was to evaluate the $(3+1)_C$ configuration using a left-hand side-stick controller instead of a conventional collective lever. In particular, a comparison of Controller 1 (stiff) and Controller 2 (deflection) mounted on the left as a vertical controller was desired. Vertical axis control was accomplished through the longitudinal axis of the candidate controller. Right-hand control of pitch, roll, and yaw was accomplished using Controller 3.

Results of the evaluation are presented in Figure 20. The left-hand deflection controller improved pilot ratings by an average of one-half point compared to the stiff controller. Level 1 ratings were achieved with an attitude command system (AT/AT or AT/LV) in pitch and roll for all low speed tasks. Pilot performance was particularly improved during the bob-up task where accurate control of aircraft height was required. Pilots found that collective control forces and small height changes were easier to modulate if small deflection was provided in the left-hand vertical controller. Based on these results, Controller 2 was selected as the primary left-hand vertical controller for subsequent evaluation of the $(3+1)_C$ and 2+1+1 controller configurations for both low and high speed tasks.

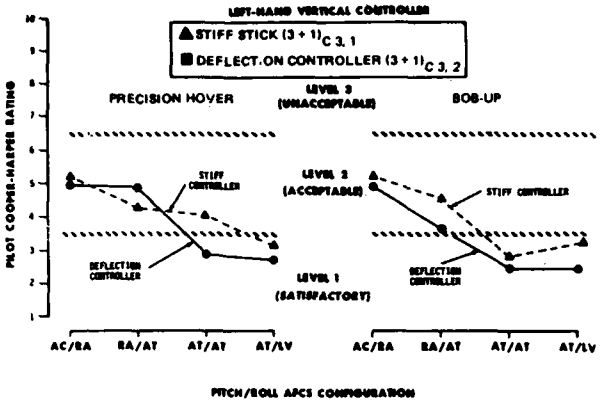

Figure 20. Comparison of (3 + 1) Collective Controller Configurations

CONTROLLER/AFCS CONFIGURATION EFFECTS - LOW SPEED TASKS

Pitch and Roll AFCS Configurations

A summary of results obtained for variations of pitch and roll AFCS and controller configurations is shown in Figure 21 for the low speed tasks--NOE, precision hover, and bob-up. Data in Figure 21 were obtained with yaw rate command/heading stabilization and vertical velocity command/altitude stabilization.

For all low speed tasks the $(4+0)_1$ and $(4+0)_2$ controller configurations received pilot ratings that were degraded approximately one rating point compared to the $(4+0)_3$ configuration. The $(4+0)_3$ controller configuration provided Level 1 ratings of approximately 3.0 to 3.5 with the higher levels of pitch and roll command and stabilization. With the same AFCS configurations, i.e. AT/AT and AT/LV, the $(4+0)_1$ and $(4+0)_2$ controllers achieved Level 2 pilot ratings of approximately 4.0. In general, higher AFCS stabilization levels for all controllers significantly reduced the effects of inadvertent control inputs or aircraft upsets, and less stabilized AFCS configurations increased pilot workload.

The effects of separate vertical and yaw controllers--$(3+1)_C$ and (2+1+1) configurations--were evaluated for all the low speed tasks. Figure 21 shows that pilot ratings for the best 4-axis controller, $(4+0)_3$, the $(3+1)_C$, and the (2+1+1) controller configurations were essentially equal for the NOE and bob-up task. Level 1 ratings were achieved for higher levels of AFCS stabilization. For the precision hover task separation of controllers had a more significant effect on pilot ratings. An improvement in pilot ratings was achieved with the (2+1+1) controller configuration which received ratings of 2.0 to 2.5 for the precision hover task. At reduced AFCS stabilization levels, this trend was not as evident.

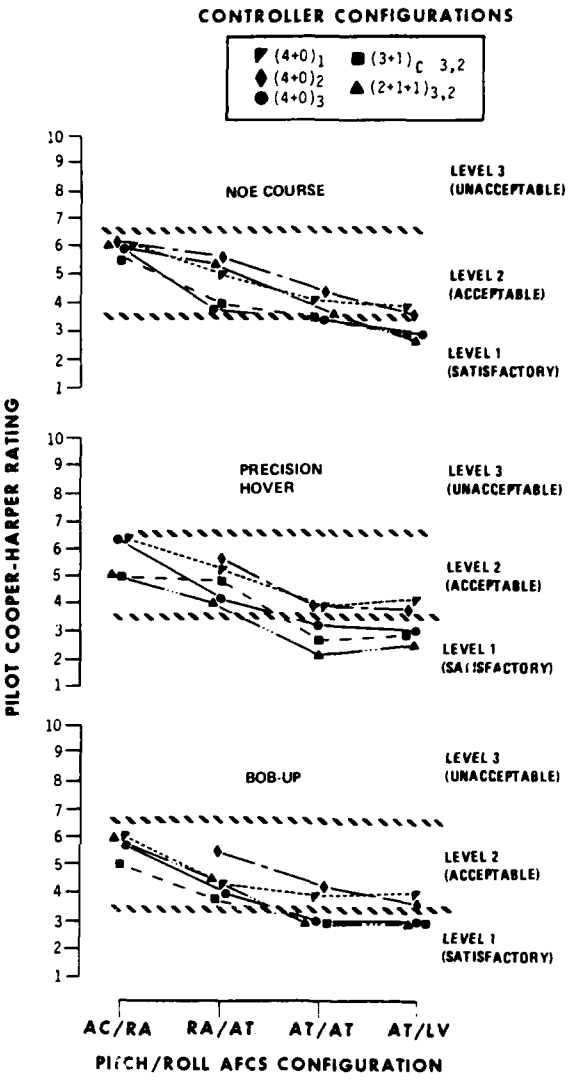

Figure 21. Pilot Ratings for Low-Speed Tasks

Yaw and Vertical AFCS Configurations

Figures 22 and 23 present a comparison of AFCS configuration changes in the yaw and vertical axes. The effects of switching from yaw rate to yaw acceleration command (heading hold off) or vertical velocity to vertical acceleration command (altitude hold off), was defined for all controller configurations; however, emphasis was given to the $(4+0)_3$ and $(3+1)_{C3,2}$ configurations.

Yaw AFCS--A yaw rate command/heading hold system was preferred by all pilots for all evaluation tasks. Level 1 ratings were achieved for this directional control system with pitch and roll attitude command configurations, i.e. AT/AT and AT/LV. With a yaw rate command

system, the pilots could modulate yaw rate precisely and make deadbeat heading changes with low workload. Yaw acceleration command made it very difficult for the pilots to achieve a desired yaw rate, and multiple control inputs were required to control the helicopter to a desired heading. Yaw acceleration control, especially during yaw reversals, lacked precision and gave a feeling of increased yaw inertia.

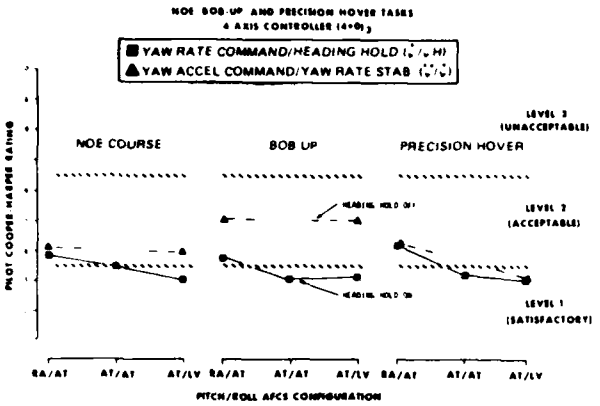

Figure 22. Effect of Directional AFCS Variations on Pilot Ratings

The effect of yaw acceleration command on pilot ratings varied with the task. Figure 22 shows that the greater the requirement for directional control during the task, the larger the degradation of pilot ratings. The precision hover task, with a minimum requirement for compensation in yaw, showed little difference in ratings. For the NOE task, where yaw inputs were required to coordinate the turns, an average degradation of one pilot rating point resulted. The bob-up task required the pilot to modulate yaw control forces accurately to arrive at a specific target heading. Pilot ratings with a yaw acceleration command system for this task degraded by as much as two rating points compared to the yaw rate command system. Level 1 pilot ratings with yaw acceleration command were only achieved for the precision hover task with a pitch and roll attitude command system. The bob-up and NOE tasks, which required larger directional control maneuvers, exhibited Level 2 pilot ratings.

Vertical AFCS--Figure 23 shows that the vertical velocity command/altitude hold system achieved the best pilot ratings in conjunction with all pitch and roll AFCS systems in the $(4+0)_3$ and $(3+1)_C$ controller configuration. Pilot comments indicated that it was difficult to modulate vertical velocity precisely with the acceleration command system. Consequently, vertical control was imprecise and required multiple reversals to attain a desired altitude. The vertical velocity command/altitude hold system made precise modulation of vertical velocity and altitude easier, thereby considerably reducing pilot workload.

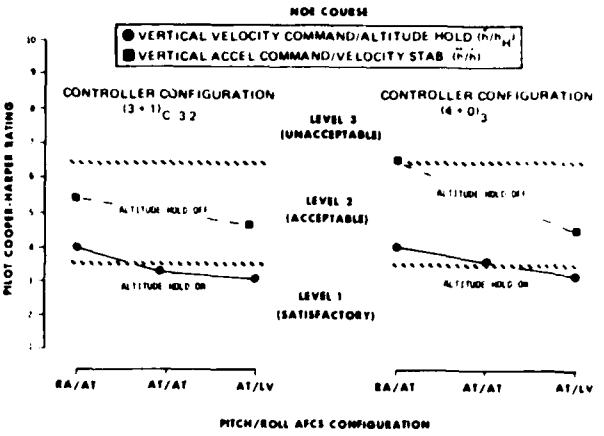

Figure 23. Effect of Vertical AFCS Variations on Pilot Ratings

Vertical acceleration control on the side-stick offered the benefit of eliminating the need to hold vertical forces to achieve a steady vertical velocity (while modulating forces in other axes at the same time). However, the benefits of altitude hold and vertical velocity command apparently offset the disadvantage of holding vertical control forces.

A comparison of data for the $(4+0)_3$ and $(3+1)_C$ controller configurations in Figure 23 indicates that for the lower level pitch and roll AFCS configurations, separating vertical control from the right-hand side-stick controller was beneficial with altitude hold off, e.g. about one rating point improvement for the RA/AT system.

CONTROLLER/AFCS CONFIGURATION EFFECTS-FORWARD FLIGHT SLALOM TASK

Slalom maneuvers were used to investigate forward flight control laws and to evaluate controller/AFCS configuration effects on handling qualities.

Pitch and Roll AFCS Configurations

The results of the 90 knot and 140 knot slalom tasks are presented in Figure 24 for three primary controller configurations. At 90 knots with turn coordination selected, the effects of controller separation were minimal. All controller configurations received comparable pilot ratings. Variations in pitch and roll command and stabilization levels showed that a combination AFCS configuration--AT/AS in pitch and RA/AT in roll--was much preferred over the other AFCS configurations evaluated. The requirement to hold heavy forces in a turn with a pitch and roll attitude command system (AT/AT) caused a significant degradation in pilot ratings of about 2.5 points. This AFCS configuration exhibited a severe degradation of flight path accuracy and airspeed hold, as well as a tendency toward PIO.

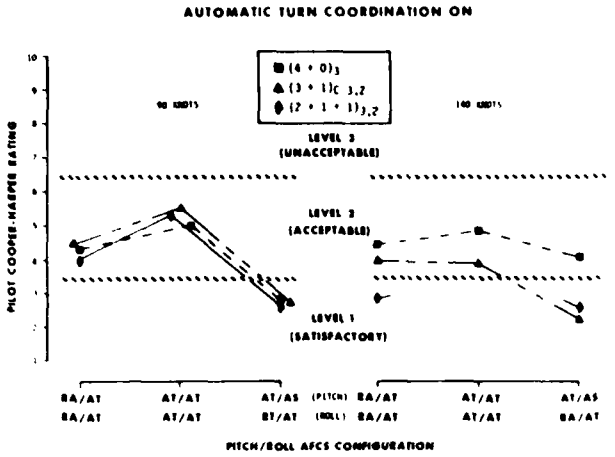

Figure 24. Pilot Ratings for High-Speed Slalom Task

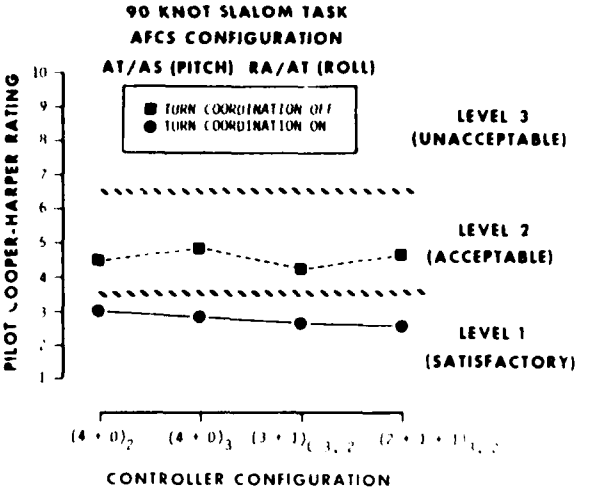

Figure 25. Effect of Automatic Turn Coordination on Pilot Ratings

The slalom task was primarily a single-axis lateral stick-steering task supplemented by pitch axis modulation to control airspeed. Automatic turn coordination and altitude hold reduced the need for compensation in the yaw and vertical axes. Therefore, any advantages of separated controllers for the slalom task at 90 knots were diminished.

This situation did not exist at 140 knots for the slalom task with automatic turn coordination on. The $(4+0)_3$ controller exhibited degraded ratings compared to the separated controller configurations. Only Level 2 ratings were obtained with the $(4+0)_3$ configuration even with the best pitch and roll AFCS configuration. Level 1 ratings were achieved for the (2+1+1) configuration with either a pitch and roll rate command system (RA/AT) or the preferred combination system (AT/AS in pitch and RA/AT in roll). The (2+1+1) configuration seemed slightly more tolerant to the higher commanded roll rates and attitudes associated with the slalom task at 140 knots.

Automatic Turn Coordination

The effect of automatic turn coordination on pilot ratings for the 90 knot slalom task is shown in Figure 25. Data are presented as a function of controller configuration for the best pitch and roll AFCS configuration--attitude command/airspeed stabilization (AT/AS) in pitch and roll rate command/attitude stabilization (RA/AT) in roll. For all controller configurations, the automatic turn coordination system improved pilot ratings by approximately 2.0 rating points, and significantly reduced pilot workload by making the slalom maneuver a single axis stick-steering control task. Level 1 ratings were achieved with all controller configurations with the turn coordination system engaged. The lack of automatic turn coordination significantly degraded flight path performance, especially at lower AFCS command and stabilization levels.

The turn coordination system designed for this simulation used lateral acceleration feedback above 50 knots to balance the aircraft automatically in turns. The system implementation appeared to have a detrimental effect on the pilots' ability to trim the aircraft with non-zero lateral acceleration. Since lateral control introduced a turn rate command into the yaw axis, it was difficult to establish steady yaw and lateral control positions required to establish an unbalanced flight condition.

CONTROLLER/AFCS CONFIGURATION EFFECTS-APPROACH TO HOVER TASKS

The experiment evaluated the benefit of blending AFCS modes in the transition region (40 to 60 knots). The transition evaluation tasks were designed to study mode switching characteristics in both a straight and a turning deceleration and descent.

Straight Descent to Hover

This task was judged the easier approach task and generally yielded improved pilot ratings compared to the turning approach to hover (Figure 26). Precise modulation of airspeed while holding a steady vertical force during the descent with a vertical velocity command system ($\dot{h}/h_H$) was difficult with the $(4+0)_3$ configuration and resulted in Level 2 pilot ratings. Flight path control was markedly improved and pilot workload reduced by separating the collective axis from the right hand controller, providing better axis identification and resulting in Level 1 pilot ratings of 2.0. The vertical acceleration command system ($\ddot{h}/\dot{h}$) eliminated the requirement to hold steady vertical forces in a descent. However, this advantage was offset by the resultant characteristics of closed-loop vertical control. There was a consistent tendency to overcontrol which

produced poor controllability and large flight path errors. Steady cross-winds had negligible effect on pilot performance and workload, regardless of the AFCS configuration.

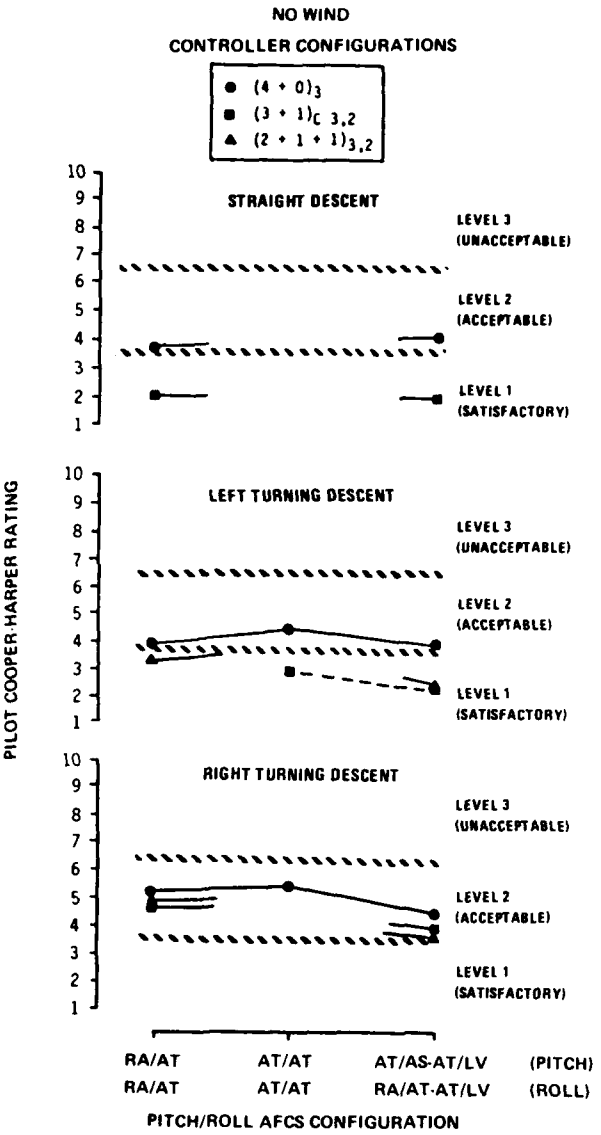

Figure 26. Pilot Ratings for Approach to Hover Tasks

Turning Descent to Hover

This multi-axis task, which required simultaneous modulation of control forces in all axes, produced degraded pilot ratings in the (4 + 0) configuration. Separation of the vertical axis with the $(3 + 1)_C$ configuration significantly reduced pilot workload by improving axis identification. Separating both the yaw and collective axes in the (2 + 1 + 1) configuration provided a further improvement in pilot performance.

Figure 26 shows a degradation of pilot ratings for right turning approaches compared to left turns. Anthropometric characteristics of the human wrist make it easier to turn the wrist (or twist the grip) to the left rather than the right. As a result, it was more difficult to modulate or hold right yaw control forces when coordinating a turn to the right. Experiments showed that 6.0 degrees of inboard rotation of the controller with respect to the armrest provided a more comfortable neutral position for yaw control. With this adjustment to controller orientation, pilot performance improved for right turns without degrading performance in left turns. However, pilot ratings in right descending turns were still degraded by about one rating point compared to left turns.

Level 1 pilot ratings were not achieved for any of the approach to hover tasks with the $(4+0)_3$ controller configuration. Conversely, the separated controller configurations did achieve Level 1 ratings for the straight-in and left turning approach to hover task.

During a turning descent the roll attitude command system (AT/AT) required the pilot to hold lateral control forces, as well as a vertical force, while modulating yaw and pitch control inputs. Pilot ratings for the pitch and roll rate command system (RA/AT) were slightly improved compared to the AT/AT system because the need to hold steady lateral forces was eliminated.

Generally, the effects of crosswind during a turning deceleration to hover were negligible.

CONCLUSIONS

The effects of variations in side-stick controller and stability and control augmentation characteristics on scout/attack helicopter handling qualities were evaluated using the NASA-Ames Vertical Motion Simulator (VMS) facility. Low speed, transition and forward flight mission tasks under visual flight conditions were evaluated. Conclusions from this experiment are summarized as follows:

SIDE-STICK CONTROLLER DESIGN

A 4-axis controller with small-deflection in all axes was preferred over a 4-axis stiff-stick design, or a design having limited deflection in the pitch and roll axes. Limited deflection improved the pilot's ability to modulate single-axis forces, produced less tendency for overcontrol and input coupling, and enhanced control precision for high-gain tasks such as precision hover.

CONTROLLER CONFIGURATION

4-Axis Controller

With a high level of stability and control augmentation, satisfactory handling qualities were achieved for the low-speed tasks investigated using the preferred small-deflection 4-axis

controller. However, the 4-axis configuration exhibited degraded pilot ratings compared to the separated controller configurations for:

- Multi-axis control tasks, such as precision hover and a decelerating turning approach to hover, and for a high-speed slalom maneuver.
- Reduced levels of stability and control augmentation.

Separated Controller Configurations

The separated controller configurations achieved similar overall pilot ratings which were generally improved compared to the integrated 4-axis controller configurations for the lower levels of stability and control augmentation investigated. For the higher levels of augmentation, either separated controller configuration was preferred for the high speed slalom maneuver and the descending decelerating transition task. Separation of both vertical and directional control was particularly advantageous for the precision hover task.

AFCS DESIGN

Pitch and Roll AFCS

For low speed maneuvering and precision hover tasks, an attitude command/velocity stabilization system provided satisfactory handling qualities for all controller configurations.

In forward flight satisfactory ratings were achieved with a hybrid combination of control laws consisting of pitch attitude command/airspeed stabilization in longitudinal and roll rate command/attitude stabilization in lateral.

Yaw and Vertical AFCS

Heading and altitude stabilization were beneficial for all tasks. Yaw rate and vertical velocity command systems were preferred for all tasks and controller configurations.

Control Law Mode Switching

To achieve the desirable low speed and forward flight handling qualities without pilot selection, the control laws required automatic phasing during transition as follows:

- Longitudinal - Attitude command/inertial velocity stabilization for low speed and attitude command/airspeed stabilization at high speed.
- Lateral - Attitude command/inertial velocity stabilization for low speed and rate command/attitude stabilization at high speed.
- Directional - Full-time heading hold for low speed and turn coordination in forward flight.

The method developed to switch control laws felt natural to the pilot. No undesirable effects on handling qualities were evident during transition maneuvers.

ACKNOWLEDGEMENTS

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